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A hadronic explanation of the lepton anomaly

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Abstract. The rise in the positron fraction, observed by PAMELA, *Fermi*-LAT and most recently by AMS-02, has created a lot of interest, fuelled by speculations about an origin in dark matter annihilation in the Galactic halo. However, other channels, e.g. antiprotons or gamma-rays, now severely constrain dark matter interpretations, thus requiring astrophysical sources of positrons. We have investigated the possibility that supernova remnants, the most likely sources of Galactic cosmic rays, can in fact also produce a hard spectrum of secondary positrons, by spallation and acceleration at the shock. This mechanism is guaranteed if hadronic CRs are present and would also lead to observable signatures in other secondary channels like the boron-to-carbon or antiproton-to-proton ratios. If such features were borne out by upcoming AMS-02 data, this would rule out other explanations.

1. Introduction

In propagation models of galactic cosmic rays (GCRs), the positron fraction, i.e. the ratio of positrons to the sum of electrons and positrons, is expected to fall at all energies. Its rise, first observed by PAMELA [1], later confirmed by *Fermi*-LAT [2] and most recently by AMS-02 [3], has been widely speculated to be of exotic origin, namely due to annihilation [4] or decay [5] of dark matter (DM) in the Galactic halo. However, since the discovery of this positron anomaly, a lot of effort has been devoted to testing this possibility in other channels with the result that DM interpretations are now severely constrained: A related rise in the antiproton-to-proton ratio (\bar{p}/p) has not been observed, thus constraining the coupling of DM to quarks [6]. The non-observation of inverse Compton gamma-rays at intermediate latitudes from additional CR electrons and positrons severely constrains the annihilation of DM into leptons [7]. Finally, the annihilation of DM into lepton final states can also be tested in the CMB which is now setting competitive bounds on the annihilation cross-section in the relevant mass range (see, e.g. [8]).

Among the astrophysical interpretations—see [9] for an overview—pulsar wind nebulae (PWNe) have received a lot of attention. Electrons are extracted from the surface of the neutron star in intense magnetic fields, get accelerated in the magnetosphere and their curvature radiation creates electron-positron pairs which can be further accelerated by the nebula's termination shock. Whereas the spin-down power and age (and possibly also the distance)



can be determined from radio observations, the efficiency of electron-positron production, the spectral index and the cut-off energy are mostly free parameters and are thus oftentimes fixed by hand to fit the observed lepton fluxes. Modelling of the lepton data has been attempted under the alternative assumptions that either only one (at most a few) nearby pulsar(s) or the whole galactic population of pulsars contribute(s). It has been argued [10, 11, 12] that a clear indication of this model would be the observation of a dipole anisotropy (in positrons) in the direction of the nearest pulsar. There is, however, a caveat. For a fixed spatial distribution of the CR density, the amplitude of the anisotropy is proportional to the *local* diffusion coefficient whereas what is obtained from measurements of secondary-to-primary ratios, like boron-to-carbon (B/C), is the diffusion coefficient, spatially averaged over large regions in the Galaxy. Furthermore, in the last couple of years it has become apparent that anisotropies in hadronic CRs are not well understood: The dipole anisotropy observed between tens of TeV and up to a few PeV is much smaller than expected from diffusion models. Even more puzzling, the sky maps of arrival directions seem to contain angular power on much smaller scales, possibly pointing at the limitations of diffusion models. We conclude that the observation of a dipole anisotropy in leptons, related to the presence of a nearby PWN is very uncertain and therefore cannot be used as a test or even diagnostic of such a model.

In the following, we focus on a particular minimal and testable model [13, 14]: minimal in so far as no new class of CR sources is required; testable because the rise in the positron fraction is mirrored in similar features in other secondary-to-primary ratios, like B/C [15, 16, 17] or \bar{p}/p [18, 17]. It is commonly assumed that supernova remnants (SNRs), the most likely candidate sources are depleted of certain species, so-called secondaries, which only get produced by spallation during the propagation of primaries through the interstellar medium (ISM). The amount of secondaries produced *inside* the sources is usually ignored since the grammage experienced by primaries inside the source is much smaller than the grammage experienced in the Galaxy (see, however, [19]). What this argument ignores is the possibility that the secondaries could have a harder spectrum than their parent primaries which could lead to an observable secondary spectrum at higher energies despite the small total number. Here, we revisit this model in light of new AMS-02 data [20, 21, 22, 23]. To avoid possible inconsistencies between results from different experiments, we focus on AMS-02 data alone.

2. Acceleration of secondaries

In the following we briefly recap the results for the spectrum of primaries and secondaries at a SNR shock in the test-particle approximation; for details see, e.g. [17]. The usual diffusion-convection equation is separately solved in the upstream ($x < 0$) and downstream ($x > 0$) of a SNR shock with shock speed u_- . In the test-particle approximation, the ratios of densities and speeds upstream and downstream, i.e. the compression factor, $r = n_+/n_- = u_-/u_+$, determines the spectral index of primaries, $\gamma = 3r/(r - 1)$. The steady-state phase-space density at the shock computes as

$$f_i^0(p) = \int_0^p \frac{dp'}{p'} \left(\frac{p'}{p} \right)^\gamma e^{-\gamma(1+r^2)(D_i(p)-D_i(p'))\Gamma_i^-(p)/u_-^2} \left[\gamma(1+r^2) \frac{D_i(p')}{u_-^2} q_i^0(p') + \gamma Y_i \delta(p' - p_0) \right], \quad (1)$$

and the spatial dependence on the downstream side is given by

$$f_i^+(x, p) = f_i^0(p) + r(q_i^0(p) - \Gamma_i^- f_i^0(p)) \frac{x}{u_+}. \quad (2)$$

Here, D_i is the diffusion coefficient, Γ_i^- the rate of inelastic collisions upstream and $q_i^0 = \sum_{j>i} c\beta_j n_- \sigma_{j \rightarrow i} f_j^0$ is the source term for secondary species i by spallation of heavier species

Table 1. Parameter values of the two models adopted in our analysis, both for the source (K_B) and for the galactic propagation (δ , κ , (dv/dz) and z_{\max}).

	K_B	δ	κ [$10^{28} \text{ cm}^2/\text{s}$]	(dv/dz) [km/s kpc]	z_{\max} [kpc]
Model 1	2,3,4	0.75	2	10	3
Model 2	9	0.65	0.6	8	1

j , with n_- the upstream gas density and $\sigma_{j \rightarrow i}$ the spallation cross section; Y_i is the abundance of primary i far upstream. It can be seen from eq. 1 that the spectrum of secondaries at the shock is harder than the injection spectrum (or the primary spectrum) due to the diffusion coefficient.

We make the simplifying assumption that after the lifetime τ_{SNR} , the integrated downstream spectrum,

$$\frac{dN_i}{dp} = 4\pi \int_0^{\tau_{\text{SNR}} u_+} dx x^2 4\pi p^2 f_i(x, p) = 4\pi p^2 V \left[f_i^0 + \frac{3}{4} r \tau_{\text{SNR}} (q_i^0 - \Gamma_i^- f_i^0) \right], \quad (3)$$

is released into the ISM. We have modelled the transport in the ISM using the GALPROP code [24] which numerically solves the transport equation for all CR species, including the production of secondaries due to spallation on the interstellar gas. As the production of secondaries in SNRs affects the secondary-to-primary ratios, like B/C, that are usually used to determine the propagation parameters, i.e. spatial diffusion coefficient κ (at a reference rigidity 4 GV), its spectral index δ or the gradient of the Galactic wind, (dv/dz) , we cannot rely on earlier determinations of these parameters. Instead we adopt a set of parameters that allows us to reproduce all AMS-02 measurements: The half-height of the diffusion volume, z_{\max} , is fixed to 3 kpc for model 1, and to 1 kpc for model 2. Solar modulation is treated in the simplified force-field approximation, allowing for different modulation potentials for different species. See Tbl. 1 for the other propagation parameters.

Among the free parameters of the source spectrum, i.e. r , u_{\pm} , τ_{SNR} , n_- as well as the diffusion coefficient $D = \beta c r_L(p)/3 \simeq 3 \times 10^{22} K_B (pc/\text{GeV}) Z^{-1} B_{\mu\text{G}}^{-1} \text{cm}^2 \text{s}^{-1}$, where $r_L(p)$ is the Larmor radius, only the combination $K_B/(u_-^2 B)$ enters into the secondary terms. We therefore fix some of the parameters, i.e. $B_{\mu\text{G}} = 1$ and $u_- = 5 \times 10^7 \text{cm s}^{-1}$, $n_- = 2 \text{cm}^{-3}$ while allowing K_B and τ_{SNR} to vary. For both models, we find $\tau_{\text{SNR}} = 4 \times 10^4 \text{yr}$ to give a good fit; K_B is shown with the other parameters in Tbl. 1. To reproduce the absolute proton and helium fluxes, the spectral index γ is also allowed to vary, but we find that $r \approx 4$ is sufficient. We note that a slightly harder Helium injection is required by the AMS-02 data which was already apparent in the PAMELA data [25]. For the primary electron injection spectrum a break has been inferred from radio data [26]; here we adopt a power-law slope of 1.6 below and 2.55 (2.65) above the break for model 1 (2). We furthermore fix the maximum energy of accelerated leptons to $E_{\max} = 10 \text{TeV}$.

Above $\sim 100 \text{GeV}$, the diffusion-loss length for leptons becomes shorter than the average distance between sources, such that lepton fluxes are very much dependent on the exact configuration of sources which is *a priori* unknown. However, one can compute statistical quantities like the expectation value from an ensemble of source distributions and the fluctuations around it. To this end we have employed the 3-dimensional, stochastic SNR mode of GALPROP, generating the fluxes for 25 realisations of a pulsar-like [27] source distribution. The shaded regions in the following figures represent the envelope of these fluxes.

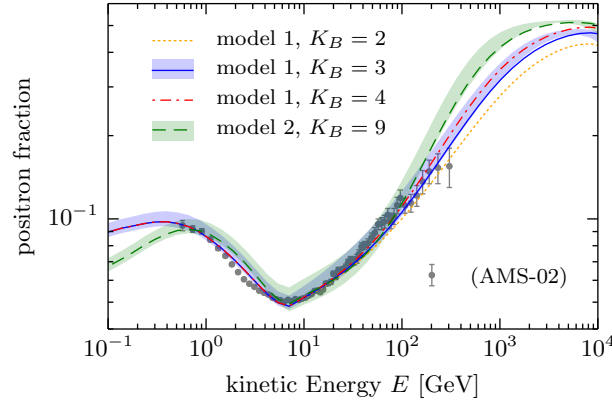


Figure 1. The positron fraction, $e^+/(e^+ + e^-)$ measured by AMS-02 [3] (circles) and for the acceleration of secondaries model with different values of the diffusion rate near the SNR shock.

3. Results

Fig. 1 shows the main result of the model, the positron fraction. It can be seen that in both models, it is falling at low energies, has a minimum around 7 GeV and rises at higher energies, in agreement with the latest AMS-02 data. Compared to earlier works [13, 18, 15, 14], the relatively milder rise in the positron fraction allows to consistently fit the absolute electron and positron fluxes, see Fig. 2. We emphasise that once the propagation parameters have been fixed,

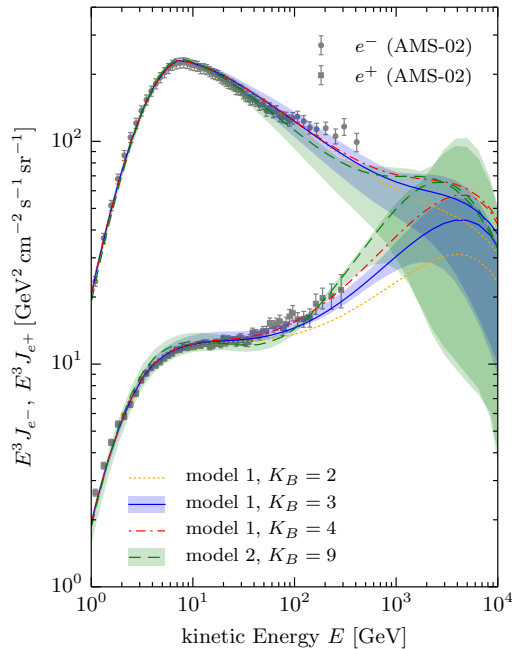


Figure 2. Absolute electron and positron fluxes measured by AMS-02 [20] (circles and squares, respectively) and for the acceleration of secondaries model.

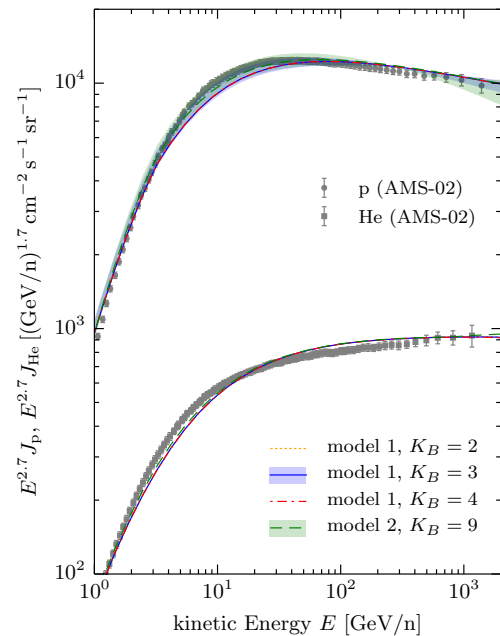


Figure 3. Absolute proton and helium fluxes measured by AMS-02 [21, 22] (circles and squares, respectively) and for the acceleration of secondaries model.

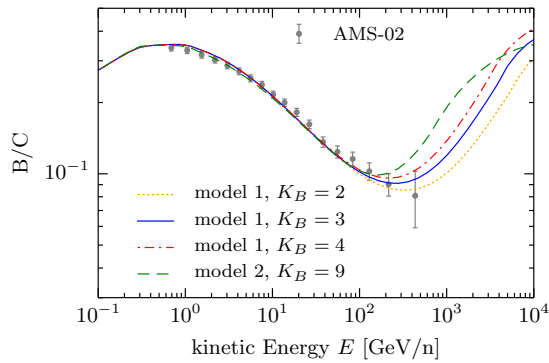


Figure 4. The boron-to-carbon ratio measured by AMS-02 [23] (circles) and for the acceleration of secondaries model.

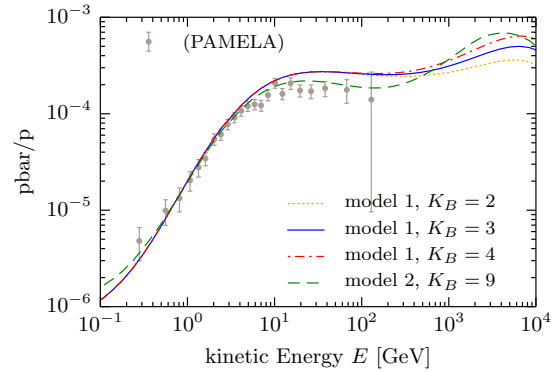


Figure 5. The antiproton-to-proton ratio measured by PAMELA [28] (circles) and for the acceleration of secondaries model.

the absolute normalisation of the electron and positron fluxes is constrained by the proton and Helium fluxes, see Fig. 3. Requiring to reproduce both at the same time therefore constitutes a non-trivial cross-check. In Figs. 4 and 5 we show the model prediction for B/C and \bar{p}/p which are affected by the production and acceleration of secondaries in a similar fashion as the secondary positrons and electrons. Two differences are however noteworthy: First, whereas the positron fraction has a minimum around 7 GeV, B/C only starts rising at hundreds of GeV. This is due to the different inelasticity of positron and boron production (positrons are on average produced at $1/20$ of the proton energy whereas boron retains the energy per nucleon of the parent primary) and the break in the electron spectrum. Second, \bar{p}/p exhibits a distinctive plateau between 10 GeV and hundreds of GeV. Whereas the contribution from the spallation in the ISM is falling at lower energies for the positron fraction or B/C , it is still rising below ~ 10 GeV for \bar{p}/p . The additional hard component from the secondaries produced and accelerated near the SNR shock therefore leads to a plateau rather than a minimum.

We note that unlike Ref. [29] we explored a larger parameter space for the propagation model, allowing for $\delta = 0.65 - 0.75$ as is expected in diffusion-convection models [30]. This allows us to fit the positron fraction without violating the constraints set by B/C or \bar{p}/p . The upcoming data on \bar{p}/p from AMS-02 and future B/C data will allow to further test this minimal model and all other possible explanations of the rising positron fraction.

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